

A ROTATING ELECTRICAL TRANSFER DEVICE

Ryan S. Porter*

ABSTRACT

This paper describes the design, development, and performance characteristics of two roll-ring configurations - a roll ring being a device use in transferring electrical energy across a continuously rotating or oscillating interface through one or more flexible rolling contacts, or flexures. Emphasis is placed on the design problems and solutions encountered during development in the areas of flexure fatigue, contact electroplating, electrical noise, and control of interface geometry. Also, the present status of each configuration is summarized.

INTRODUCTION

A roll ring consists of one or more flexures captured by their own spring force in the annular space between two concentric conductors, or contact rings. Figure 1 shows a photograph of each configuration. These inner and outer contact rings are rigidly mounted to the rotating and fixed sides of the rotating axis.

Two basic roll-ring configurations are presently under continuous research: the single flexure, 0- to 15-amp configuration and the multiflexure, 0- to 200-amp, high-power design.

The single circuit shown in Figure 1A is typical of over 400 circuits with a cumulative test history of approximately 600,000 circuit-hours, tested under several parameter-controlled conditions in an effort to optimize operational performance.

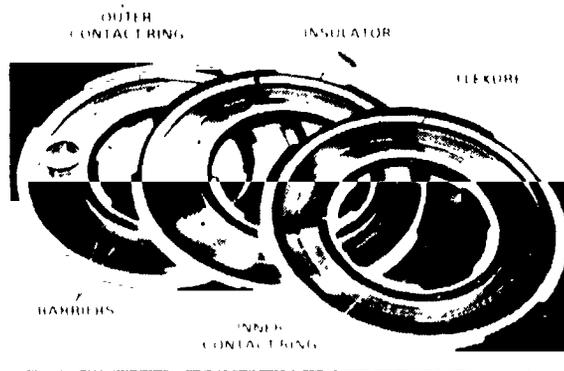


Figure 1A. Single-Flexure, 15-Amp Roll-Ring Circuits

*Sperry Corporation, Aerospace & Marine Group, Space Systems Division, Phoenix, AZ

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At present four high-current designs have been fabricated and at least partially evaluated. Figure 1B is a plan view of one circuit in an 8-circuit module that was designed and fabricated.

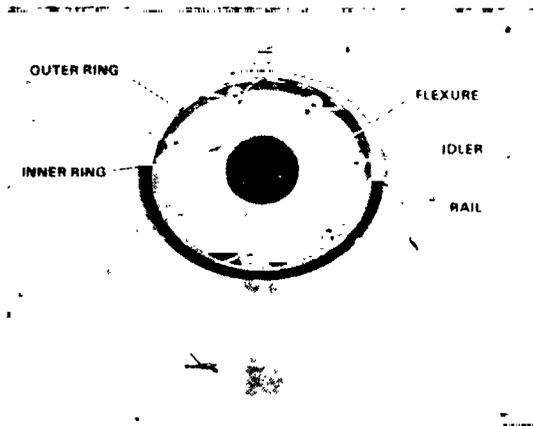


Figure 1B. Multiflexure High-Current Configuration

DEVELOPMENT OF 15-AMP DESIGN

Very little information was available when research and development began on this rolling-contact interface. The bulk of available literature dealt with sliding contacts (as in slip rings) or with make/break devices (as in switches). It was, therefore, necessary to empirically determine the design sensitivities of this new technology.

Flexure Fatigue

Early in the development of the 15-amp flexure, a fatigue failure at 30 million reverse bending cycles indicated that either the stress model or the allowable stress limit was incorrect. After the stress model was carefully scrutinized and exonerated, the material properties were investigated.

Flexures are machined from beryllium copper alloy 172 and subsequently precipitation-hardened for optimized mechanical properties. The published fatigue stress data used in designing the flexure deflection limits were derived from Beryllco's strip stock results and ASTM rotating beam testing. Their respective S/N curves are shown in Figure 2. The cold-rolled processing gives the strip and rod stock a preferred grain orientation. This preferred grain orientation enhances the fatigue properties of the material when stressed along the grains (Ref 1). During operation, a flexure is stressed across the grain, its weakest axis (as summarized in Figure 3). Therefore, an S/N curve for beryllium copper in an operating flexure's stress orientation was needed to select an acceptable fatigue stress for a long-life flexure design.

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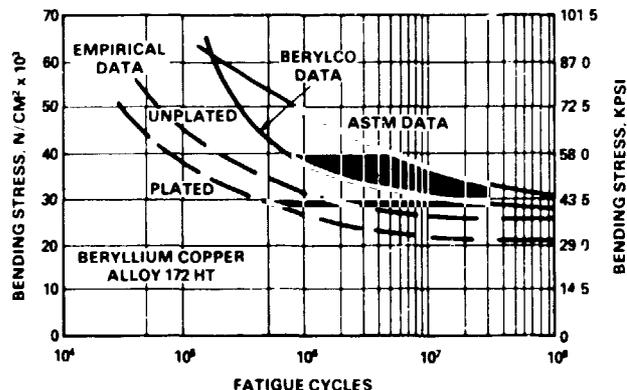


Figure 2. Fatigue Curves for Various Testing Configurations

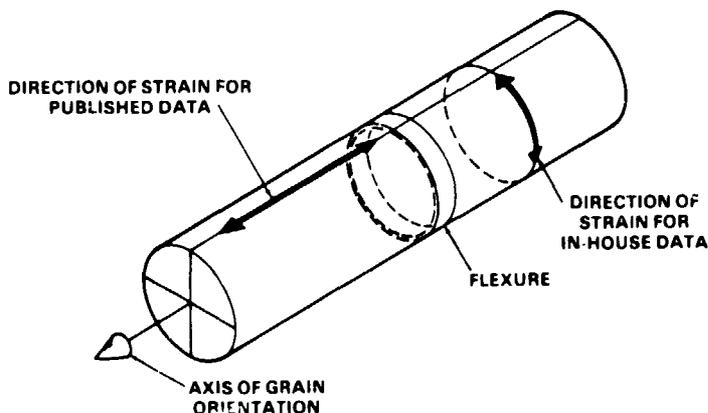


Figure 3. Strain Axes of Cold-Rolled Flexure Material

This curve was established by subjecting nearly 60 specimens to reverse bending in proper stress orientation at various stress levels until a predetermined number of cycles was achieved or fracture occurred. To accelerate the testing, an oscillating driver was used for cycle accumulation, with a quartz load cell and accelerometer used to determine load and displacement. The test setup is shown in Figure 4. Some development was required to arrive at a satisfactory means of holding the specimen so as not to introduce uncharacteristic end restraints on the test specimens. Mechanical schematics of the initial and final test configurations are shown in Figure 5. The initial configuration introduced a nonrepeatable clamping arrangement, making data correlation impossible. The final configuration schematic (in Figure 5) shows how the test specimens were ultimately configured to compensate for fixture deficiencies. By removing a portion of the flexure, its stiffness was reduced by an order of magnitude, permitting higher induced stresses at a lower amplitudes and higher frequencies, permitting collection of a greater number of data points in a given amount of time.

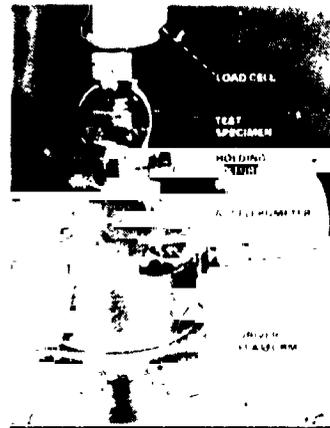


Figure 4. Fatigue Test Setup

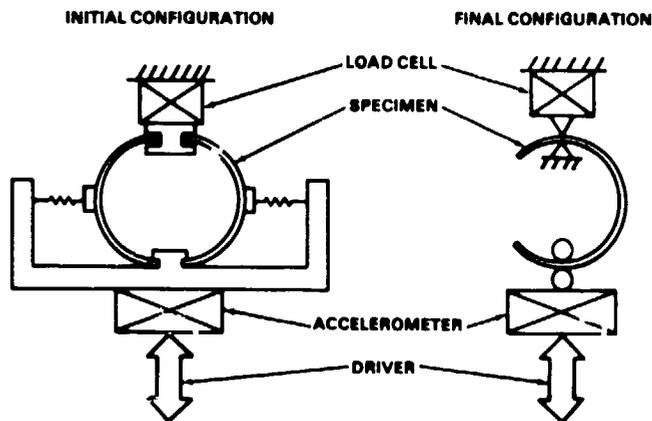


Figure 5. Fatigue Test Mechanical Schematic

Once the fixturization had been established, an S/N plot was generated. The specimens were subjected to various heat-treat schedules and plating-thickness matrices. The results are shown in Figure 2. To date, not one in over 400 properly designed flexures has experienced a fatigue failure, even though some have undergone more than 35 million reverse bending cycles.

In addition to preferential grain orientation, cold-rolled stock has properties that vary with distance from the surface; i.e., the percentage of grain area reduction (or cold working) decreases with the distance from the surface (Ref 1). Since mechanical properties improve with the amount of cold work, the nearer the material is to the surface, the higher are its mechanical properties. Therefore, flexures are made from rod stock that is nearest the finished diameter of the flexure.

Interface Geometry and Fabrication

The roll-ring design must assure dynamic stability of the flexure(s) while running in, and captured by, the ring grooves. The stability of the flexure relates to its inherent ability to remain aligned in the grooves during rotation. In general, the stability diminishes as the annulus width ($R_0 - R_1$) approaches the sum of the ring contact groove radii (R_G), as shown in Figure 6, or:

$$\frac{2 R_G}{(R_0 - R_1)} < 1$$

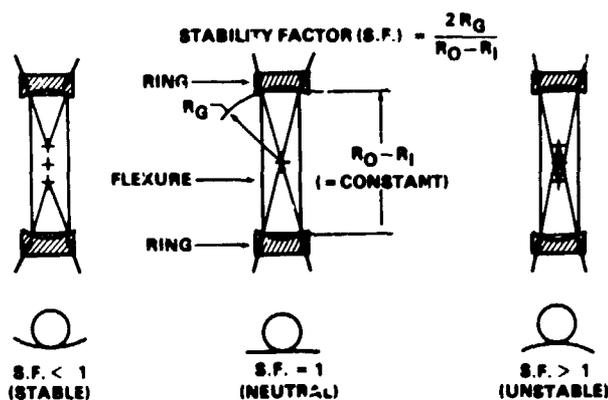


Figure 6. Stability Factor of Flexure/Ring Interface

Today's test units have a stability factor of approximately 0.22, which provides excellent operational stability.

The conformity of the interface is a definition of the degree to which the radiussed edges of the flexure (r_f) nest in the ring groove radius (R_G). This geometry is similar to a ball bearing. It is important for the roll ring, not only for its effect on contact stress, but for its influence on contact resistance as well. As r_f approaches R_G , the conformity approaches 100 percent, at which the contact stress is a minimum because of maximized contact area. This also yields minimum contact resistance.

The flexure began as a pure rectangular section. However, the resultant excessive contact stresses promoted premature wear-through of the gold-plated interface. The second generation incorporated chamfered corners which, although easy to fabricate, resulted in inconsistent interfaces. At this point, radii were applied to the flexure corners with close tolerance controls on their center locations.

Initial efforts to apply the radius on a lathe were unsuccessful because it was difficult to locate the radius centers by hand. Therefore, blanks with rectangular sections were made and the radii added in a different setup with a form tool. Special tooling had to be developed that could hold the blank without runout or distortion. This process proved acceptable, but tended to be operator-sensitive and could only provide parts with the surface finish and accuracy of the form tool. Also, because of tolerance sensitivity, the conformity could be reliably maintained at about only 50 percent.

The final solution, in standard practice today, was to manufacture the flexures on a numerically controlled lathe with very low feed rates, large cutter diameters, and empirically determined cutting sequences - resulting in surface finishes of less than 0.2 micrometer. The accuracy and repeatability of numerically controlled machinery provide a reliable means of producing, in today's designs, conformities in excess of 90 percent.

Conductor Plating

Several different plating materials and combinations of materials on contact rings and flexures have been evaluated from the standpoint of electrical noise and wear.

Most of the plating configurations studied are variations on a nickel and gold matrix on both contact rings and flexures. In almost all cases a copper flash is plated onto the substrate (brass for rings and beryllium copper for flexures) for adhesion purposes. This is then overplated with 2.5 to 4.0 microns (100 to 150 microinches) of a sulfamate nickel as a copper migration barrier and as a hard underlayer for the gold to follow. The nickel is then overplated with the same thickness of either a hard alloy gold or a soft pure gold. Gold was selected for its excellent electrical properties and corrosion resistance.

Ion plated and electroplated rhodium configurations were also evaluated with very little success. Rhodium is a strong catalyst for the formation of polymers in the presence of organics. Since it is difficult to eliminate all sources of organic contamination, particularly in a vacuum environment, it was concluded that rhodium was an inherently poor choice as a roll ring conductive overplate. This was demonstrated by exceptionally poor electrical performance, although wear resistance was excellent because of its exceptional hardness.

It was thought that by plating very thick (25 microns or 1000 micro-inches) layers of gold onto the rings and the flexures, the contact area could be maximized by allowing the flexure and rings to mold themselves into each other. The gold used (3el-Rex BDT-200) turned out to be too hard to permit adequate mating, and the excessive thickness resulted in unacceptably high flexure bending stresses.

One source of flexure fatigue in early testing was thought to be residual stresses in the nickel layer. Some flexures were, therefore, plated without nickel. This theory proved incorrect. However, without the nickel as a migration barrier, the circuits developed excessive electrical noise, thought to be due to metal oxides on the surface.

Thick copper plating beneath the nickel was tried in an attempt to improve the "imbedibility" of random contact anomalies. No disposition was arrived at, but difficulties in plating such thick layers of copper prompted abandoning that approach.

Nominal plating thicknesses of pure soft gold on both flexures and rings seemed suitable to provide low noise, but wear was marginal for long-life applications (one million revolutions) because of the high ductility of pure gold. The gold in the contact zones of the rings and flexures would be partially displaced, and some of these gold extrusions would sometimes break loose, forming conductive debris. Although some debris was generated, it amounted to 2 or 3 orders of magnitude less volume than that found in a slip ring assembly with even a fraction of the travel. As flexure fabrication techniques and conformity improved, the tendency for extrusion was reduced - particularly with the lower stress, lower preload flexure designs. Today's configurations generate virtually no debris, even for very-long-life applications.

A noise mechanism was hypothesized that correlated high friction to electrical noise. It was also reported that increased hardness reduces friction (Ref 2). Therefore a matrix using hard-gold-plated rings and soft-gold-plated flexures was tried. This configuration resulted in improved wear because of less extruding, but no significant noise improvement was detected.

The last and most recent configuration under study is hard-gold flexures on hard-gold rings. The wear is practically nonexistent, but the contact resistance tends to be somewhat higher because of the reduced contact area and higher resistivity of the hard-gold alloy.

The present status indicates that several of the nickel-plus-gold configurations may be adequate for most applications if appropriate preloads and conformities, which are now routine, can be maintained. The configurations to avoid are those that create high bending stresses in the flexure (plating thickness in excess of 25 microns (1000 microinches)), those that use catalytic materials for polymer formation (rhodium, platinum, palladium, etc.), and those that allow metal oxides to form (plating that is too thin to prevent wear-through, is subject to porosity, or has a migration barrier eliminated).

The question arose of cold-welding of a gold-on-gold interface. Since the friction coefficients of most metallics increase in vacuum, the frictional forces of sliding members also increase to the point that friction-welding can occur under certain conditions (Ref 3). Another welding phenomenon is associated with the molecular adhesion of ultraclean, highly stressed interfaces under very special laboratory conditions (Ref 4).

Thousands of hours of vacuum tests of the roll ring under simulated application configurations for static, dynamic, and dither modes of operation have not shown any tendencies toward cold-welding. This fact is attributed to the mainly rolling interface, the gold contact materials, the contact stress level, and the nonsputter-cleaned surfaces. This determination is made on the basis of both visual and elemental evaluations of post-test items using SEM/EDXA procedures.

DEVELOPMENT OF 200-AMP DESIGN

In 1979 an application requiring a 60-amp capability for a single circuit launched the development of the high-current/high-power design presently under intense investigation. This configuration incorporates a full complement of flexures in the annulus space of a single circuit to handle the increased current loads. It contains a unique idler system for maintaining angular spacing between adjacent flexures.

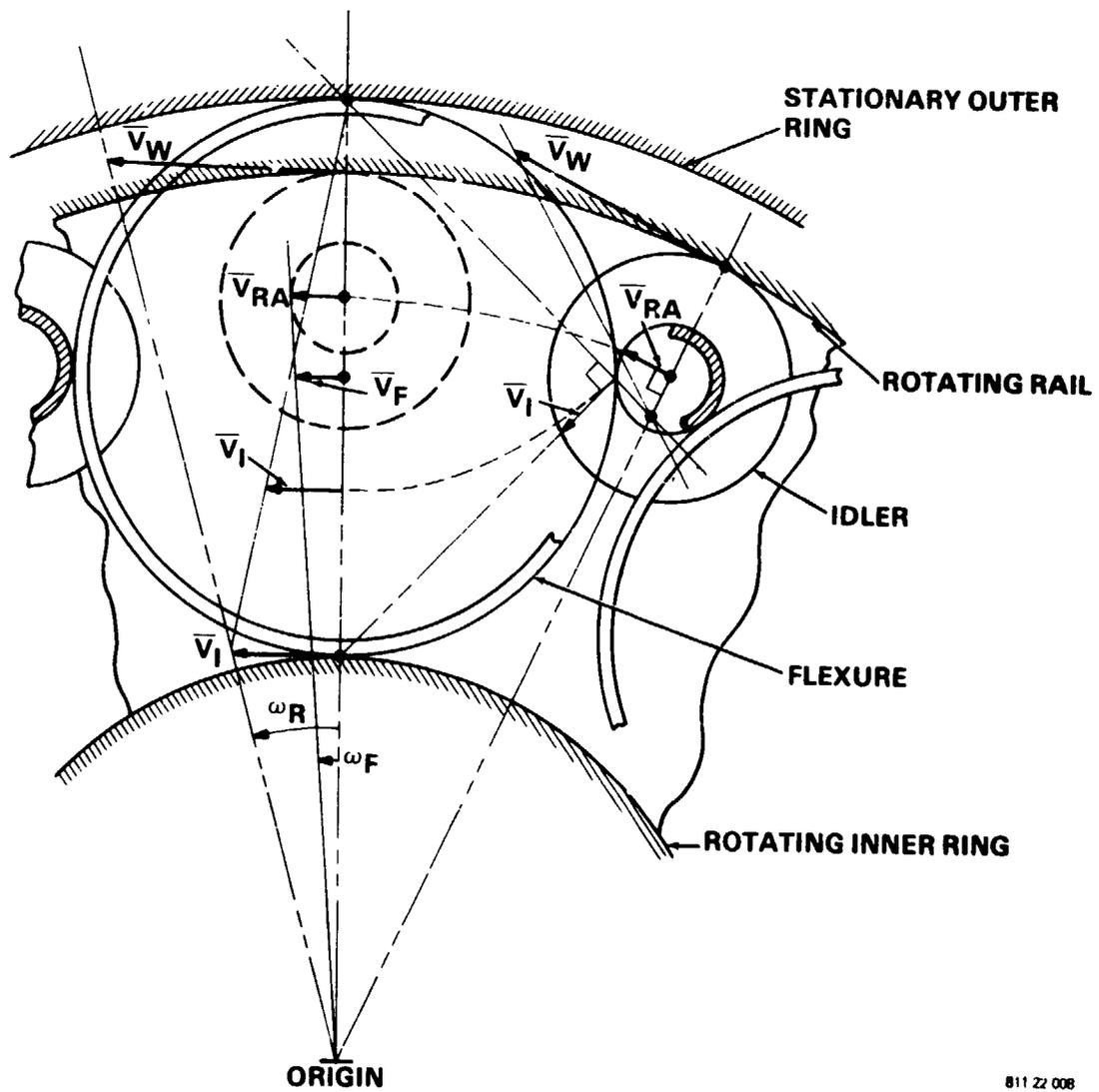
Multiflexure Spacing

When a high-current design was first approached, several flexures were evenly spaced in the same ring set to distribute the current load among them, the number of flexures governed by the current capacity requirements. During rotation, however, tolerance variations allowed the flexures to move circumferentially with respect to one another so that two or more flexures eventually came into contact, resulting in unmitigated sliding at the line of contact. Flexure damage occurred as a result of the high sliding friction coefficient.

The idler concept emerged as the means to maintain circumferential spacing without sliding. These idlers are guided by the flexures, and roll on a set of rails that are mechanically attached to the inner ring assembly. A unique set of roller diameters exists for every set of flexure and ring diameters. These are analytically determined by matching instantaneous velocity vectors of the flexures and rollers at points of mutual contact. Figure 7 identifies the graphic representation of these various velocity vectors.

Mechanical and Electrical Isolation

Although a high degree of mechanical isolation exists in the 15-amp design due to the insulator geometry (shown in Figure 1A), the mechanical isolation is taken a step further for the multiflexure, high-current designs. These are also being designed to withstand voltage potentials near 500 volts in order to obtain power transfer capacities on the order of 100 kilowatts. This is accomplished by selecting appropriate materials and geometry, as well as preventing line of sight between conductive surfaces or materials.



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Figure 7. Vector Definition for Flexure/Idler Velocity Match

The primary concern when designing high-voltage systems is electrical breakdown, which manifests itself as corona or arcing. Although 500 volts, by most power standards, is not considered particularly high voltage, it is still above the minimum spark voltage of 240 volts RMS and requires special attention.

Corona is not a critical concern since all applications studied to date operate in a vacuum environment, and a gaseous ambient is required to support corona. Therefore, by providing adequate ventilation of the module, the internal pressure can be maintained below the regime required to sustain corona - especially if system voltages are kept down to 500 volts or lower.

However, since some ground testing invariably occurs at atmospheric pressure, the use of overlapping barriers to prevent line of sight provides labyrinths that result in relatively large air gaps. These labyrinths are included primarily to inhibit arcing (by providing a torturous path for an arc), as well as to keep out external debris.

To inhibit arc susceptibility, a dual insulator system is used between adjacent conductors. The primary insulation consists of a glass-filled resin that has a high dielectric strength (15.6 V/ m, 400 V/mil). This is used for axial as well as radial insulation. The secondary insulation is provided by teflon-impregnated, hard anodized aluminum. The teflon impregnation tends to fill the pores typically present in a hard anodized coating, resulting in a very reliable insulator.

The teflon-filled coating (designated Hardtuf by the supplier, Tiodize Co, Inc.) produces a very low friction surface for structural parts, which permits smoother assembly of close-fitting components.

Thermal Considerations

When transferring high power (10 to 100 kilowatts), a prominent operating parameter of the system is transfer efficiency. The transfer efficiency (e_T) is defined as the percentage of power transferred through the rotating interface without thermal loss and is given by

$$e_T = \frac{EI - I^2R}{EI} = \frac{E - IR}{E}$$

where E = source voltage, volts
 I = system current, amps
 R = circuit resistance, ohms

Given a circuit with fixed current and supply voltage, the designer may maximize the transfer efficiency by minimizing the circuit resistance. In the case of a roll ring, this is accomplished by increasing the number of parallel contacts, or flexures, in a given circuit. The measured circuit resistance of the most recent, 10-flexure configuration is approximately 0.38 milliohm under current load. The circuit resistance is about 20 percent higher during a low-current, four-wire measurement because of film effects. Therefore, the transfer efficiency under 500-volt, 200-amp condition is

$$e_T = \frac{500 - 200 \times .00038}{500} \times 100\% = 99.985\%$$

However, even with transfer efficiencies this high, thermal losses are generated because of the finite circuit resistance. At maximum current, the development module generates approximately 15 watts per circuit; so that, being an 8-circuit assembly, it converts 120 watts of power to thermal energy which must be managed.

Since this device operates in a vacuum, the primary modes of heat transfer are conduction and radiation. Therefore, geometries were selected to maximize the contact area of adjacent components, and materials with high heat-transfer coefficients were used for fabrication.

Besides providing secondary insulation, the hard anodized aluminum rails provide an axial heat conduction path for the thermal energy in the rings as well as a radial path for the roller/rail heat-transfer interface. The roller, in turn, is acting as a partial sink for the flexures.

Although the test setup was not configured to model the radiation mode of heat transfer seen in flight operation, the hard anodized housings provide high-emissivity surfaces to act as radiators should a receiver be present.

In an effort to predict the temperature profile of a unit in operation, a thermal model is being developed and the thermal resistances are being determined empirically. Several interface resistances must be determined empirically because very little literature exists on the interface characteristics of various material combinations. Because of the symmetric nature of the plan view of a multiflexure circuit, a lumped analytical approach is used (i.e., the characteristics of all 10 flexures can be thermally equated to a single flexure with appropriate coefficients).

In the model, only the current-carrying components are considered active, heat-generating components: those consisting of the contact rings, connecting bolts, flexures, and their contacts. Since the contact resistance of this particular gold-on-gold interface can be directly measured and the materials used are well documented, the Q (rate of heat generation) and K (thermal conductivity) terms can easily be determined. However, hundreds of empirical measurements are necessary to determine the remaining terms. At the writing of this paper, this work is still in progress.

ELECTRICAL NOISE

Electrical noise is defined as resistance transients of the electrical interface that occur during operation. This is distinguished from steady state resistance, which is a function of the material properties and remains constant. Several applications, however, can tolerate various levels of electrical noise - characterized by amplitude, duration, wave shape, and frequency of occurrence.

During the course of several years of investigation, a variety of mechanisms that may or may not cause electrical noise have been theorized and proven or disproven. Several of these studies and conclusions are included here for the benefit of the reader. It should be pointed out that, although these mechanisms may behave as described herein for a roll ring - which uses conformal rolling interfaces - they may behave differently when applied to conceptually different devices.

Organic Films

It is believed that, for a roll ring, the presence of an organic film does not cause electrical noise under most conditions. Indeed, the presence of a large quantity, as in an oil film, actually benefits the electrical performance for signal current levels. Though organics are by nature primarily nonconductive, their viscous properties permit a flexure with sufficient mechanical preload to make electrical contact-either by complete displacement of the film or by partial displacement to a thickness that will permit conduction by tunneling.

There are exceptions, however. In the presence of large quantities of a viscous organic, experience has shown that currents exceeding 3 amps may cause breakdown of the organic into less viscous insulators that will not permit efficient conduction. Also, viscous films result in hydroplaning of the contact at elevated rotational rates. The speed at which transition occurs is a function of both flexure preload and film viscosity. These results were compiled during testing of contacts intentionally lubricated with a variety of lubricants.

Stick Slip

It was suggested that the high friction coefficient of gold-on-gold in vacuum was permitting the flexure to edge up the ring groove until some surface anomaly initiated a "skid" back into the bottom of the ring groove. During the "skid" the contact surfaces were thought to separate elasto-hydrodynamically. After much study and investigation, it is felt that this is a very improbable mechanism.

First, a stick-slip mechanism implies a fairly random nature with unpredictable periods. However, whenever a roll-ring circuit is experiencing resistance transients, it can almost always be traced to the defect period of an outer ring, inner ring, flexure, or combination thereof.

Second, stick slip is a dynamic condition that can occur only during actual rotation or oscillation. However, it is sometimes possible to "park" on an area of increased resistance.

Third, there has been no visible physical evidence of such an action. Gold, being exceptionally malleable, would leave some sort of a transverse scratch in the gold that has never been seen. The only noncircumferential markings that have been observed on the rings are epicyclic swirls associated with the entry and exit paths of the flexure contact across the footprint's finite width.

Fourth, stick slip is by nature a very rapid event that would have a distinct repeatable time-history wave shape. Roll-ring noise tends to be randomly shaped and of various durations despite its often periodic nature.

Preload

Experience has shown that there is very little correlation between flexure preload and electrical noise. Preloads as low as 0.09 newton (0.02 lbf) and as high as 2.0 newtons (0.45 lbf) have yielded low noise performance. The preload does have a small effect on dc contact resistance, which is to be expected since a higher preload establishes a larger footprint and hence lower resistance. Finite deflection and therefore finite preload is necessary, however, to ensure running stability. Typical 15-amp flexures today have preloads of 0.22 to 0.36 newton (0.05 to 0.08 lbf) and deflections around 0.6 mm (0.025 in.).

Polymers

As mentioned earlier, the only instances that nonconductive polymers were encountered were when rhodium was used as part of the plating matrix. It was discovered during testing that rhodium is a very good catalyst for polymer formation for a roll ring in the presence of organic films or vapors. Since organic vapors are habitually present in vacuum systems because of the outgassing of several materials, polymers did form on the roll ring and poor electrical performance resulted. However, to date, no indications of polymers have been detected when a gold-on-gold system has been used.

Silicon

A high correlation was found between the presence of silicon in the system and resultant electrical noise. Although the exact form of the nonconductive film containing silicon was never identified, several sources of silicon contamination were eliminated from the test system, resulting in greatly improved electrical performance. The primary source of silicon contamination was the result of operating fixture drive motors with silicon-grease-lubricated gear-heads in the vacuum chamber with the circuits under test.

Metallic Oxides

Recently, a correlation between electrical noise and codeposited copper in the gold has been established. Copper is a very active metal that oxidizes readily and has a tendency to migrate (Ref 5). That is why a nickel migration barrier is generally included in most gold-plating matrices.

Most gold-plated electrical contacts can tolerate a small level of copper in the gold because they quite often have wiping actions that scrape away any oxide layers before making contact. This may explain why small amounts of active metal contamination would not alarm a plating vendor. However, the roll ring does not have an aggressive wiping action and is therefore more sensitive to the presence of oxide films on the contact surface. Once this is known by the plater, it is a relatively simple matter to control the active metal contaminants and so reduce or eliminate the presence of metallic oxide films.

Surface analysis techniques have been, and are, invaluable tools for investigating resistive films. The Scanning Electron Microscope (SEM) has provided a great deal of visual support and some help in identifying bulk materials on the contact surface through Energy Dispersive X-ray Analysis (EDXA). However, the electron beam has a finite penetration that does not permit analysis of very thin surface films. To examine very thin surface films (0 to 100 Angstroms), Electron Spectroscopy for Chemical Analysis (ESCA) is used. ESCA is the only surface analytical technique that provides direct information on the chemical (as well as elemental) nature of the atoms in an unknown sample (Ref 6). For three-dimensional mapping of various elements in a sample, Auger Electron Spectroscopy (AES) is used in conjunction with sputter etching. ESCA demonstrated the presence of copper on the surface, while AES determined that it was codeposited with the gold rather than a result of migration or a surface condition only.

SUMMARY

A great deal of development has been completed, and is in progress, relative to a rolling electrical contact device that is uniquely suited for signal/power transfer in present and future space applications. Several technology areas had to be enlarged, resulting in new knowledge in a variety of areas. This virgin technology has provided two configurations of the roll-ring mechanism that demonstrate not only a very low torque capability but reduced resistivity and a high voltage capability as well.

A design and performance summary of the two configurations is given in the listing below:

ROLL-RING DESIGN SUMMARY

| Parameter | Single Flexure | Multiflexure |
|-----------------------|-------------------------------|--|
| Current Capacity | 15 amp | 200 amp |
| DC Circuit Resistance | 10 milliohms | 0.4 to 0.5 milliohm |
| Peak Electrical Noise | 50 milliohm goal ^a | 3 milliohms |
| Life | 10 ⁷ revs (proven) | 10 ⁷ revs (theoretical) |
| Torque per Circuit | 1.4 x 10 ⁻⁴ N-M | 3.5 x 10 ⁻³ N-M (10 flexures) |
| Weight per Circuit | 35 grams | 900 grams |
| Transfer Efficiency | 99.50% (15 A, 30 V) | 99.985% (200 A, 500 V) |

REFERENCES

1. Spotts, M. F. 1971. Design of Machine Elements, 4th ed. Englewood Cliffs, NJ: Prentice-Hall, Inc.
2. Antler, M. March 1974. Wear of Gold Plate: Effect of Surface Films and Polymer Codeposits. Trans IEEE, Vol PHP-10, No. 1.
3. Cuthrell, R. E., and D. W. Tipping. May 1973. Factors That Affect the Solid-Phase Bonding of Gold Wire Electrical Leads. Sandia Laboratories Report SLA-73-0535.
4. Cuthrell, R. E., and D. W. Tipping. December 1972. Electric Contacts: Equipment and Mechanics of Closure for Gold Contacts. Sandia Laboratories Research Report No. SC-RR-72-0783.
5. Antler, M. March 1973. Tribological Properties of Gold for Electric Contacts. Trans IEEE, Vol PHP-9, No. 1.
6. Evans, Charles A., Jr., and Richard J. Blattner. 1978. Modern Experimental Methods for Surface and Thin-Film Chemical Analysis. Annual Reviews Inc, p. 199.
7. Patent No. 4,372,633. 8 February 1983. High Current Transfer Roll Ring Assembly.

^aDevelopment in this area, although converging rapidly, is not yet complete. Therefore, a definitive value for peak electrical noise is difficult to reference.